Aerosol distribution and efficacy in a commercial food warehouse

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Abstract A series of field trials were conducted in a commercial food storage facility to evaluate exposure of stored-product insects to aerosol formulations of synergized pyrethrins and the insect growth regulator methoprene. When adults of *Tribolium castaneum* (Herbst), the red flour beetle, and *Tribolium confusum* (Jacqueline DuVal), the confused flour beetle were exposed with and without a food source to synergized pyrethrin aerosol, there was no difference in adult mortality with respect to availability of food at either 7 or 14 days after exposure ($P \geqslant 0.05$). However, mortality was lower in *T. confusum* (40.4% and 79.3% with flour at 7 and 14 days, 38.9% and 84.8% without flour at 7 and 14 days) compared to *T. castaneum* (96.5% and 99.8% with flour at 7 and 14 days, 91.0% and 98.7% without flour at 7 and 14 days). Few late-stage larvae and pupae of either species exposed to the pyrethrin aerosol emerged as adults. In tests with methoprene aerosol, adult emergence of exposed 3- and 4-week-old larvae of *T. confusum* was less than 2%. Only 0.3% of 4-week-old larvae of *T. castaneum* exposed in open and obstructed areas emerged as adults. Emergence of adults from eggs of *Plodia interpunctella* (Hübner), the Indianmeal moth, embedded in culture media and exposed to the methoprene aerosol was 13.2% ± 3.5%. Results show that the aerosols evaluated in our study could give effective control of some of the major stored-product insect pests in commercial food storage facilities, and may offer an alternative to fumigation.

Key words aerosols, control, methoprene, *Plodia*, pyrethrin, *Tribolium*

Introduction

The fumigant methyl bromide is being withdrawn from production under the terms of an international agreement known as the Montreal Protocol (Taylor, 1994; Fields & White, 2002; Anonymous, 2004). The current phase-out schedule specifies elimination of methyl bromide by 2005 in the USA and other developed countries, and by 2015 in undeveloped countries. However, exemptions were made for all quarantine uses (Kawakami, 1999), and a process was established where user groups could receive critical use exemptions (CUEs) (Anonymous, 2004). In the USA, methyl bromide has been an important insect control measure in flour mills, processing plants, and food warehouses, and CUEs have been approved for some usage of methyl bromide in mills and warehouses. There are alternative fumigants available, but they have limitations. Phosphine generally cannot be used in these types of facilities because it is corrosive to metals and electrical equipment (Bond *et al.*, 1984). Sulfuryl floride is registered as a fumigant in the USA and several countries in the European Union, but there may be some economic issues involved when used at the dosage rates necessary to kill eggs of stored-product insect. With all fumigants, there are safety issues to consider. The facility undergoing a fumigation must be shut down and ventilated after application, and precautions must be made when fumigating structures surrounded by commercial buildings and private residences. For all of these reasons, the use of fumigants in some structures may not be feasible, particularly if these structures are located in urban areas.

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One of the alternatives to methyl bromide and other fumigants is aerosol insecticides, also known as fogging or space sprays (Peckman & Arthur, 2006; Campbell & Arthur, 2007). In contrast to methyl bromide, aerosols have limited penetration ability and primarily affect only exposed insects, but they are far less costly to apply than methyl bromide and do not have the safety risks associated with fumigants. However, there is a lack of published data regarding the distribution and efficacy of current aerosol formulations that is relevant to large commercial food storage facilities. The organophosphate insecticide dichlorvos has been used in the USA as an aerosol treatment in food storage facilities (Childs, 1967; Gillenwater *et al.*, 1971; Cogburn & Simonaitis, 1975), but the re-entry period required after treatment, plus the fact that dichlorvos is a neurotoxic insecticide, may limit the widespread adoption and use in active commercial facilities.

Synergized pyrethrins, which are a mixture of natural pyrethrins plus a synergist, have been used on a limited basis for many years, and there are several newer formulations registered in the USA for use inside food warehouses. Similarly, the insect growth regulator (IGR) methoprene can also be used as an aerosol to control stored-product insects. However, active commercial facilities contain spatial barriers such as pallet stacks of products and goods, which may affect the dispersion of aerosols. There are currently no published studies in which new pyrethrin formulations or methoprene have been evaluated inside an active commercial food storage facility. In one recent study, adults of *Tribolium confusum* (Jacqueline DuVal), the confused flour beetle, were exposed to an aerosol formulation of pyrethrin in an empty commercial warehouse, with and without flour (Arthur & Campbell, 2008). Although the aerosol was effectively distributed throughout the warehouse, some adult *T. confusum* were able to recover from knockdown, depending on where the adults were exposed, and in addition, the presence of the flour food source led to an increase in recovery and survival to the aerosol. Results from studies with contact insecticides also show increased survival of *Tribolium* adults when provided with a flour food source either during or after insecticide application (Arthur, 1998, 2000). It is apparent that sanitation plays an important role in the overall efficacy of a pest management program, but this role may often be unrecognized.

One of the challenges in field evaluation of aerosols is locating commercial sites that would allow stored-product insects to be brought inside their facilities for exposure trials. In this study, a series of field trials were conducted inside a commercial food storage facility to: (i) evaluate aerosol dispersion and efficacy in an actual field setting; (ii) determine relative susceptibility of several stored product insects and life stages to selected insecticides; and (iii) determine if insect response differed when exposed in open versus obstructed sites.

Materials and methods

Tribolium castaneum and T. confusum exposed to pyrethrin aerosol

In 2004, tests were conducted in a large commercial food bank with a space volume of approximately 142 860 m^3. A complete aerosol application system, which dispensed aerosol insecticides at an approximate particle size of 15 microns, was installed inside the facility by Entech Systems (Kenner, Louisiana, USA). This application system could be operated manually or through a timer, and individual storage rooms within the larger facility were equipped with aerosol dispensing lines and nozzles so that different areas within the larger facility could be treated separately.

The aerosol trials were conducted inside a large storage room measuring approximately 69.2 m length by 23.1 m width by 10.8 m height (17 264 m^3). There were two dispensing nozzles hung from the ceiling at approximately 17 m from each end along the long axis of the room (Fig.

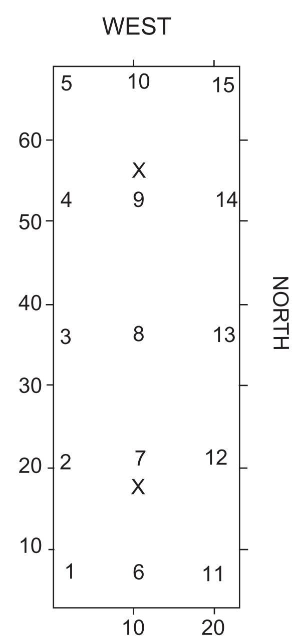

Fig. 1 Approximate positions where *Tribolium castaneum* and *T. confusum* adults and immatures were exposed to pyrethrin and methoprene aerosol inside a storage room within a commercial facility. Dimensions of length and width are in metres. An "X" denotes the approximate position of the two spray nozzles.

1). The experimental unit was the bottom portion of a standard plastic Petri dish, which measured approximately 89 × 15 mm (area 62 cm^2), which was painted white and lined with filter paper to minimize any potential effect of repellency by the plastic in the dish. The test insects were 4-week-old larvae, pupae, and adults of *Tribolium castaneum* (Herbst) and 4-week-old larvae, pupae, and adults of *T. confusum*. All immature and adult insects were maintained in colonies cultured at the Grain Marketing and Production Research Center (GMPRC), Manhattan, Kansas, USA. Both species were collected from eastern Kansas, USA, in 1958 and had been maintained at the GMPRC since that time at 27 ± 1°C, 60% ± 2% relative humidity. Beetles were reared on a mixture of 95% whole-wheat flour and 5% brewers yeast.

For each of six replicate trials, two sets of dishes containing either 10 adults of each beetle species, in separate dishes either with 250 g of whole wheat flour or without flour (4 dishes total) were placed at 15 locations within the room (Fig. 1). In addition, separate dishes containing either 10 4-week-old larvae of each species, or 10 pupae, with 250 mg of flour (4 dishes total for immatures), were placed in the same positions. The dishes containing the insects were prepared at the laboratory and transported by car to the testing site on the day of the test. The five positions in the center were in open areas equidistant from the side walls, and spaced approximately 17 m apart. The five positions along the side walls were spaced in the same manner, but were within 0.3 m of the wall. The room was estimated to be occupied by 10% inventory, and although the positions of the stacked goods constantly changed, the volume occupied by the inventory remained the same for all six replicates. The insecticide used in the trials was Entech Fog-10, a 1% active ingredient (AI) pyrethrin formulation (2% composition of piperonyl butoxide synergist), with a labeled maximum application rate of 23.4 g of formulation/28 m^3 of headspace. The space occupied by the inventory was subtracted from the total area, and the application rate was calculated based on the area of the unoccupied headspace. At each treatment, 80% of the maximum use rate was applied in the room.

The six replicate trials were conducted on 6, 7, 13, 14, 20, and 21 October, 2004. At each trial, separate sets of dishes were placed in the warehouse office as untreated controls, along with the dishes exposed to the aerosol as described above. The actual time required for the aerosol system to dispense the required amount of insecticide was approximately 20 minutes, and the timer was set to shut the system down upon completion of this time interval. The dishes were left in position overnight and picked up the next morning, and returned to Manhattan, where they were held on a counter in a climate-controlled laboratory at approximately 25°C. At 7 and 14 days post-treatment, adults in the dishes were examined and classified as running (survival), knocked down (on their backs and moving) or dead (failure to move when touched with a probe). Dishes containing the immature life stages were held until 7−10 days after all immatures in the untreated control dishes had emerged as adults.

The General Linear Models (GLM) Procedure of the Statistical Analysis System (SAS, 2001) was used to analyze the data. Species, exposure position, and the presence of the flour food source were considered main effects, and the 7- and 14-day counts for variables survival, knockdown, and mortality was a repeated measure. Because of variation in the data set, means were transformed by square-root and analyses were performed on the transformed variables. In addition, because of the large number of positions, analyses for differences between exposure positions were performed using Bonferonni analysis to account for experiment-wise error in the data set. Data for immature stages were analyzed with species and exposure position as main effects, with adult emergence as the response variable.

Tribolium confusum *larvae exposed to methoprene aerosol*

In 2005, tests were conducted in the same test room within the commercial facility described above. At each of the 15 exposure positions (Fig. 1), ten 3- and 4-week-old *T. confusum* larvae prepared in separate Petri dishes as previously described were exposed to methoprene aerosol (Diacon II, Central Sciences International, Dallas, Texas, USA). The formulation is 240 mg AI/mL, and the label specifies application at 3 mL of formulation per 280 m^3 of headspace area, calculated as also described in the previous section.

Six separate replicate trials were conducted on 22 and 23 June, 10 and 11 August, and 26 and 27 October. The aerosol system was set to apply the desired amount of the methoprene formulation, and again approximately 20 minutes was required to dispense the aerosol. The dishes containing the larvae were left overnight and picked up the next morning. At each trial, 10 dishes each of 3- and 4-week-old larvae were placed in the untreated office as controls. All dishes containing larvae were returned to the GMPRC laboratory, and held until approximately 1 week after all adults had emerged in the respective control dishes. Criteria for evaluation were the emergence of normal healthy adults, with no visible morphological effects associated with exposure of beetle larvae to methoprene and other insect growth regulators. Data were analyzed statistically using procedures in SAS as described above.

Aerosol efficacy in open and obstructed areas

In 2006 tests were conducted by exposing 10 4-week-old larvae of *T. castaneum*, prepared in separate Petri dishes as previously described, in 10 open and 10 obstructed positions within the test room of the commercial facility. This species was used instead of *T. confusum* because the results from the first experiment showed that *T. castaneum* is more susceptible to methoprene than *T. confusum*. Using the more susceptible species would allow observance and determination of differences between the open and obstructed sites. These open sites were in approximately the same position in the center of the room as described before, closer to the side walls, but all were placed in the relative center of the room, approximately 9 m from the north and south side walls (Fig. 2). The sites that were categorized as obstructed were underneath pallet loads of goods, approximately 1–2 m away from the open sites. Dishes containing the larvae were pushed underneath the pallet, approximately 0.3–0.6 m from the edge. At the same positions where the dishes with the *T. castaneum* larvae were located, a separate set of dishes was placed which contained approximately 8 g of culture media and 10 eggs of *Plodia intepunctella* (Hübner), the Indianmeal moth in each dish (10 dishes total in the open and 10 in the obstructed positions). The *P. interpunctella* strain was collected from Savannah, GA, USA, before 1969 and was maintained at the GMPRC at 27 ± 1°C, 60% ± 2% relative humidity since the original collection. The moth media used for the colony cultures is of dry ingredients: 1 774 mL of cracked wheat, 2 838 mL of wheat shorts, 26 mL of wheat germ, 17 mL of brewer's yeast, and 5 mL each of sorbic acid and benzoic acid; and wet ingredients: 240 mL of honey, 240 mL of glycerin, and 120 mL of tap water. All ingredients are thoroughly hand-mixed to form the colony media. The colonies were occasionally supplemented with individuals from the wild on a sporadic basis.

Three replicate trials were conducted with *T. castaneum* larvae on 14 and 15 June, and 18 July, while four replicate trials were conducted with *P. interpuctella* eggs on 15 June, 18 July, and 15 and 16 August. At each trial, 10 dishes containing either *T. castaneum* larvae with flour and 10 dishes containing *P. interpuctella* eggs with media, were exposed in the untreated office to serve as controls. The methoprene aerosol was applied as described for the 2005 tests. All statistical analyses were performed as described previously.

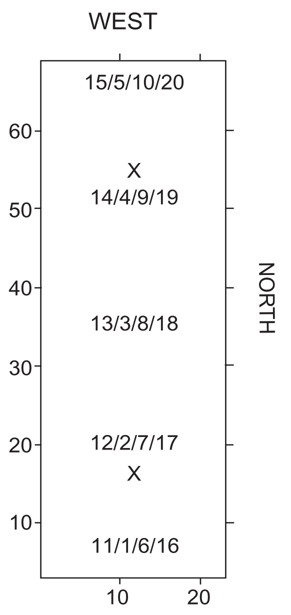

Fig. 2 Approximate positions where 4-week-old *Tribolium castaneum* larvae and *P. interpuctella* eggs were exposed to methoprene aerosol inside a storage room within a commercial food storage facility. Positions marked 1–10 are in open areas of the floor, positions marked 11–20 were placed approximately 0.3–0.5 m underneath a pallet of stacked goods. Dimensions of length and width are in metres. An "X" denotes the approximate position of the two spray nozzles.

Results

Tribolium castaneum *and* T. confusum *exposed to pyrethrin aerosol*

There was little mortality or knockdown of adults of either *T. castaneum* or *T. confusum* in untreated controls, and survival was virtually 100%. No corrections for mortality were necessary. The percentage of beetles that survived the aerosol exposure was significant for main effects species ($F = 11.5$; df = 1,266; $P < 0.01$) and position ($F = 2.5$; df = 14,266; $P < 0.01$), plus the repeated measure time ($F = 4.9$; df = 1,284; $P < 0.01$), but not the presence of the flour food source ($F = 2.1$, df = 1,266, $P = 0.15$). The only significant interaction was species × food ($P < 0.01$, all others $P \geqslant 0.05$). The percentage of survivors at 7 and 14 days post-treatment was less in *T. castaneum* than in *T. confusum* when they were provided with the flour food source, and there was no difference in survival of either species between 7 and 14 days post-treatment regardless of the presence of the food source (Table 1).

The percentage of beetles that were classified as knocked down was significant for species ($F = 330.4$; df = 1,266; $P < 0.01$), time ($F = 259.6$, df = 1,284, $P < 0.01$), and the presence of the flour food source ($F = 4.7$, df = 1,266, $P = 0.03$), but not position ($F = 1.6$; df = 1,266; $P = 0.07$). Both

Table 1 Percentage survival (means ± SE), knockdown (KD) and mortality of *Tribolium castaneum* and *Tribolium confusum*, 7 and 14 days after exposure with and without flour†, to 1% active ingredient (AI) pyrethrin aerosol inside a commercial food storage facility. The pyrethrin aerosol was applied at the labeled rate of 23.4 g formulation/28 m^3 of headspace area‡.

	With flour	7 days	14 days
Survival	*T. castaneum*	2.3 ± 1.0 bA	0.1 ± 0.1 bA
	T. confusum	13.1 ± 3.3 aA	9.5 ± 2.7 aA
Knockdown	*T. castaneum*	1.2 ± 0.6 bA	0.0 ± 0.0 bA
	T. confusum	46.5 ± 4.3 aA	1.2 ± 2.4 aB
Mortality	*T. castaneum*	96.5 ± 1.2 aA	99.8 ± 0.1 aA
	T. confusum	40.4 ± 4.4 bB	79.3 ± 2.8 bA
	Without flour		
Survival	*T. castaneum*	3.5 ± 1.4 aA	1.3 ± 0.7 aA
	T. confusum	4.5 ± 1.7 aA	3.7 ± 1.7 aA
Knockdown	*T. castaneum*	5.4 ± 1.2 bA	0.0 ± 0.0 bB
	T. confusum	56.6 ± 4.2 aA	11.4 ± 2.6 aB
Mortality	*T. castaneum*	91.0 ± 2.2 aB	98.7 ± 0.7 aA
	T. confusum	38.9 ± 4.3 bB	84.8 ± 3.2 bA

†Adult emergence in from 3- and 4-week-old larvae in untreated controls was 98.4% ± 0.7% and 96.7% ± 11.7%, respectively.

‡Differences in percentage survival, knockdown, and mortality for each species, with and without flour, between 7 and 14 days post-exposure are significantly different ($P < 0.05$, Proc *t*-test, SAS) when denoted by different upper-case letters. Differences in percentage survival, knockdown, and mortality between each species, with and without flour, at 7 and 14 days post-exposure are significantly different ($P < 0.05$, Proc *t*-test, SAS) when denoted by different lower-case letters.

the time × food and the time × species × food interactions were significant ($P < 0.01$), but no other interactions were significant ($P \geqslant 0.05$). Knockdown can be considered a transitional category between survival and mortality, but there were considerably fewer *T. castaneum* that were knocked down compared to *T. confusum*; however, at both 7 and 14 days, the percentage of *T. confusum* that were knocked down decreased regardless of whether they were held with or without flour (Table 1).

The analysis for percentage mortality was significant for species ($F = 206.1$; df = 1,266; $P < 0.01$), position ($F = 2.1$; df = 1,266, $P = 0.02$) and time ($F = 176.3$, df = 1,284; $P < 0.01$) but not the presence of the flour food source ($F = 0.2$, df = 1,266, $P = 0.89$). Only the species × time × food interaction was significant ($P < 0.01$, all others $P \geqslant 0.05$). Percentage mortality was always less in *T. confusum* populations than in *T. castaneum* populations at the 7- and 14-day exposures (Table 1). Mortality of *T. confusum* increased between 7 and 14 days in beetles exposed with and without flour, but mortality of *T. castaneum* did not change in either case. Because of the variation in the data set, an analysis was done on the untransformed data for all three response variables with respect to the presence of food material after exposure, using non-parametric analysis (PROC NPAR1way in SAS), which performs several tests on the ranks of the response variables. There was no significant difference ($P \geqslant 0.05$) for percentage survival, knockdown, and mortality, with and without food material.

Initial analysis showed a significant effect of exposure position ($P < 0.05$) for percentage survival, knockdown, and mortality. However, the Bonferonni analysis, which takes into account experiment-wise error rate for a large number of comparisons, showed there were no differences with respect to the individual exposure positions for survival, knockdown, or mortality of either species at the 7- and 14-day exposure periods, exposed with or without food. Although there was no difference in the individual exposure groupings, it was possible that there was an effect of position with respect to a larger grouping; that is, differences in exposure dishes that had been placed along the side walls where they were often located between stacks of pallets and the walls, versus the dishes placed in the open center. To test for a center versus edge effect, data for positions 1−5 and 11−15 at the edges of the test room and positions 6−10 in the center were combined. Because the general analysis had shown no difference in the presence of food material, data for food were also combined. Data were analyzed by species, with position as a main effect and time as a repeated measure. Survival and mortality were not significant with respect to position grouping for *T. castaneum* ($F = 0.7$, df = 2,8, $P = 0.54$; $F = 1.3$, df = 2,8, $P = 0.38$), respectively, but percentage knockdown was significant ($F = 5.4$, df = 2,8, $P = 0.04$). Percentage survival was significant with respect to position grouping for *T.*

confusum ($F = 5.3$, df = 2,8, $P = 0.03$), but not percentage knockdown ($F = 2.6$, df = 2,8, $P = 0.67$) or mortality ($F = 5.3$, df = 2,8, $P = 0.13$). Results were inconsistent and did not indicate any real difference regarding whether the exposure dishes were in the center of the room compared to the side walls.

Virtually all untreated larvae of both species emerged as adults. In contrast, no immature *T. castaneum* emerged as live healthy adults in any of the treatments. Larvae were usually discolored and failed to reach the pupal stage, and exposed pupae could not emerge as adults. Emergence of *T. confusum* exposed as pupae was low and sporadic, and averaged only 0.06% ± 0.06% and 0.17% ± 0.12% after 7 and 14 days, respectively. No exposed larvae emerged as adults.

Tribolium confusum *larvae exposed to methoprene aerosol*

Emergence of normal adults from the 3- and 4-week-old larvae of *T. confusum* in the untreated controls averaged 98.4% ± 0.7% and 96.7% ± 11.7%, respectively, in all six replicates. No corrections were made for emergence in the larvae exposed to the methoprene aerosol because adult emergence in the untreated controls was probably due to random variation and did not affect any lack of adult emergence in the treatments. When the ANOVA was initially performed on the data for the 3- and 4-week-old larvae exposed to methoprene aeraosol, there was a significant block effect for replicate ($F = 17.4$; df = 5,145; $P < 0.01$), which was primarily due to random variation from larvae occasionally escaping exposure by crawling underneath the filter paper. There was no effect of position or larval age ($F = 1.7$; df = 14,145; $P = 0.06$; $F = 0.5$, df = 1, 145; $P = 0.55$, respectively), and adult emergence was 3.0% ± 0.9% in the exposed 3-week-old larvae and 4.1% ± 1.2% in the 4-week-old larvae. When data were analyzed for replicate effects, there was a significantly greater percentage of adult emergence in the 3- and 4-week-old larvae exposed in replicate 3 ($P \leqslant 0.05$; Waller-Duncan *k*-ratio *t*-test). With replicate 3 eliminated, there was no replicate effect ($P > 0.05$), none of the main effects were significant ($P > 0.05$), and adult emergence was only 0.9% ± 0.4% and 1.6% ± 0.6% from the exposed 3- and 4-week-old larvae, respectively.

Aerosol efficacy in open and obstructed areas

Adult *T. castaneum* emergence from untreated control larvae was 81.3% ± 2.3%. There was only one emerged adult in all open positions and one emerged adult from all closed positions (out of 300 exposed overall in each group) exposed to the methoprene aerosol; therefore no statistical analysis was necessary. Emergence of adult *Plodia interpunctella* from eggs in the untreated controls was 89.4% ± 2.5%. Although there were numerical differences among the positions in which the dishes containing the *P. interpunctella* were exposed (Table 2), there was no significant difference with respect to open versus closed positions ($F = 0.1$; df = 1,60; $P = 0.71$), or location of individual positions ($F = 1.7$; df = 9,60; $P = 0.10$). However, there was extensive variation in the data set with adult emergence in the treatments often being limited to one or two replicates, as indicated by the large standard errors associated with the means. This variation could have masked any potential treatment effects among the locations of the individual dishes exposed in open and closed positions.

Table 2 Percentage adult emergence (means ± SE) from Plodia interpuctella eggs exposed to methoprene aerosol† in open and obstructed positions inside a commercial food storage facility. The methoprene aerosol was applied at the labeled rate of 3 mL (720 mg active ingredient/280 m^3 of headspace area)‡.

Location	Open positions†	Obstructed positionsb‡
1	0.0 ± 0.0	2.5 ± 2.5
2	5.0 ± 5.0	0.0 ± 0.0
3	5.0 ± 5.0	0.0 ± 0.0
4	20.0 ± 12.2	10.0 ± 7.1
5	50.0 ± 28.9	47.5 ± 27.5
6	2.5 ± 2.5	5.0 ± 5.0
7	0.0 ± 0.0	12.5 ± 12.5
8	27.5 ± 24.3	15.0 ± 15.0
9	7.5 ± 7.5	45.0 ± 26.3
10	25.0 ± 18.9	45.0 ± 26.3

†Adult emergence from eggs in untreated controls was 89.4% ± 2.5%.
‡Adults emergence from all exposed eggs was 16.2% ± 3.5%.

Discussion

Results of this study show the potential for using aerosol insecticides to control stored-product insects in food storage facilities. The aerosol application system effectively distributed the aerosol particles throughout the large storage room, and penetration of the aerosol particles underneath pallets containing stacked goods was sufficient to give complete control of insects exposed in areas which did not receive direct overhead deposition. In addition, the presence of food material at the time the pyrethrin insecticide was applied did not lead to a reduction in mortality of exposed adult *T. castaneum* or *T. confusum*, which does occur when these same species have access to a food source during or after exposure to contact insecticides (Arthur, 1998, 2000). The presence of the food source could give the insects nutritional components that help to reduce the effects of the insecticide on physiological systems.

In this trial and in a previous field trial (Campbell & Arthur, 2008), adult *Tribolium* spp. were shown to be susceptible to pyrethrin aerosol, but this is the first report regarding the susceptibility of larvae or pupae to any aerosol product evaluated at actual or simulated field conditions. In field populations of *T. castaneum*, adults have been predicted to comprise less than 5% of the total population, and any adult mortality resulting from insecticidal applications may have little effect on population growth (Toews *et al.*, 2005). Impacts of aerosols, including IGRs, on the immature stages of *Tribolium* populations, would be essential for aerosols to be effectively utilized in a total management program. Although the evaluation process is complicated by the necessity of providing immatures with a food source during and after exposure to aerosols, in the current test it appeared that the aerosol particles were absorbed by the larvae through direct deposit or from the food material.

There is also a lack of published data regarding the susceptibility of the egg stage of stored-product insects to aerosol exposure. Eggs are often difficult to kill with fumigants (Bell & Savvidou, 1999) and with aerosols (White & Leesch, 1996) compared to other life stages, but there are also mitigating factors which could influence susceptibility. Stored-product insects often lay eggs in food material, and depending on where those eggs are positioned in the food material, they could escape exposure. In our test with the methoprene aerosol, we deposited the *P. interpunctella* eggs on the surface of the growth media that was inside the Petri dish, and therefore the variation in our data could have resulted from the eggs being deposited in different exposure positions relative to the surface of the media. Variation in the age of the eggs could have also resulted in differential effects, because the older eggs might be less susceptible to insecticide penetration.

The use of aerosols to control stored-product pests may be an effective alternative to methyl-bromide, and other fumigants such as sulfuryl floride, cylinderized phosphine, or carbonyl sulfide. Fumigation can be expensive, and safety considerations usually require a complete shutdown of the facility if the entire structure is to be treated. Heat treatment is an effective alternative to methyl bromide for the milling industry (Mahroof *et al.*, 2003; Roesli *et al.*, 2003), but may not be a viable option for food storage sites because of the risk of damage to finished and packaged food products. Recent studies have documented extensive populations of stored-product insects in and around mills and food storage facilities (Doud & Phillips, 2000; Campbell & Mullen, 2004; Campbell & Arbogast, 2004), which can lead to a quick population recovery after fumigation (Campbell & Arbogast, 2004; Toews *et al.*, 2006). Therefore, a more integrated management approach, which could include sanitation and the use of aerosols and contact insecticides, could yield a more consistent reduction in pest populations.

Acknowledgments

I thank B. Barnett and E. Jenson for excellent technical assistance for the research projects described in this study. I also thank Entech Systems for providing access to the commercial facility and for technical assistance with the projects. C. Burks and M. Toews reviewed this manuscript prior to journal submission, and I thank them for their comments and suggestions. This paper reports the results of research only. The mention of a proprietary product, trade name, or commercial company does not constitute a recommendation or endorsement by the U.S. Department of Agriculture.

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Accepted October 16, 2007